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## ► To cite this version:

P. T. Nastos, C. S. Zerefos. Decadal changes in extreme daily precipitation in Greece. *Advances in Geosciences*, 2008, 16, pp.55-62. hal-00297088

**HAL Id: hal-00297088**

**<https://hal.science/hal-00297088>**

Submitted on 9 Apr 2008

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# Decadal changes in extreme daily precipitation in Greece

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Received: 25 August 2007 – Revised: 17 December 2007 – Accepted: 25 January 2008 – Published: 9 April 2008

**Abstract.** The changes in daily precipitation totals in Greece, during the 45-year period (1957–2001) are examined. The precipitation datasets concern daily totals recorded at 21 surface meteorological stations of the Hellenic National Meteorological Service, which are uniformly distributed over the Greek region. First and foremost, the application of Factor Analysis resulted in grouping the meteorological stations with similar variation in time. The main sub groups represent the northern, southern, western, eastern and central regions of Greece with common precipitation characteristics. For representative stations of the extracted sub groups we estimated the trends and the time variability for the number of days (%) exceeding 30 mm (equal to the 95% percentile of daily precipitation for eastern and western regions and equal to the 97.5% percentile for the rest of the country) and 50 mm which is the threshold for very extreme and rare events. Furthermore, the scale and shape parameters of the well fitted gamma distribution to the daily precipitation data with respect to the whole examined period and to the 10-year sub periods reveal the changes in the intensity of the precipitation.

## 1 Introduction

A great scientific interest with respect to extreme precipitation events and their economic, social and ecological implications has been aroused especially during the last decades (Karl et al., 1995; IPCC, 2001; Zhang et al., 2001). According to IPCC (2001), extreme precipitation is difficult to reproduce, especially for the intensities and patterns of heavy rainfall which are heavily affected by the local scale. For this reason, it is necessary to study heavy and extreme precipita-

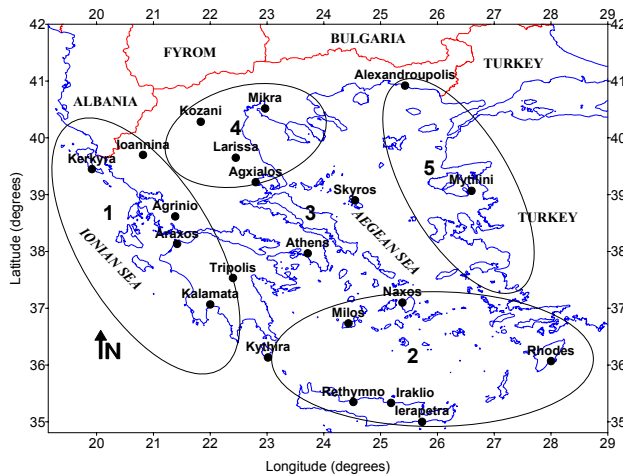
tion events by analyzing long time series of observed station data. Although regional differences are relatively high, annual precipitation trends in the 20th century, for a number of stations in Europe, exhibit a clear general positive trend for northern Europe, with the exception of Finland, and a negative for southern Europe and the Mediterranean (IPCC, 2001). Anagnostopoulou et al. (2006) studying the cyclones in the Mediterranean region, found that the Hadley Center Atmospheric General Circulation Model (HadAM3P) predicts a future decrease of the frequency of the severe cyclones (<1000 hPa) at the SLP level, but the future cyclones will be more intense, especially at the 500 hPa level.

Large changes in the wintertime atmospheric circulation have had a profound effect on regional distributions of surface temperature and precipitation. Anomalies in precipitation, including dry wintertime conditions over southern Europe and the Mediterranean and wetter-than-normal conditions over northern Europe and Scandinavia since 1980, are linked to the behaviour of North Atlantic Oscillation Index (NAOI) (Hurrell and van Loon, 1997). Besides, according to the results of Krichak and Alpert (2005), the precipitation decline over the Mediterranean region during the last decades of the past century can be explained by the positive trend in the East Atlantic Western Russia pattern, which was induced by the positive trend of the North Atlantic Oscillation. Regarding Greece, Feidas et al. (2007) found out that the observed downward trend in winter and annual precipitation in Greece is linked mainly to a rising trend in the hemispheric circulation modes of the NAOI, which are connected with the Mediterranean Oscillation Index. Moreover, low-frequency fluctuations in the circulation over the Atlantic have been closely linked to the coherent large-scale precipitation anomalies that have persisted, particularly in winter, over Turkey since the early 1960s (Turkes and Erhat, 2003).

The precipitation variability and the distribution of precipitation frequency within the Mediterranean Sea and Greece have been carried out by many researchers (Repapis, 1986;



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**Fig. 1.** Network of meteorological stations and the regions with common precipitation characteristics.

Nastos, 1993; Mantis et al., 1994; Metaxas et al., 1999; Brunetti et al., 2004; Nastos and Zerefos, 2007).

The objective of this study is to analyze the extreme daily precipitation time series recorded at 21 meteorological stations in Greece, for the period 1957–2001, by processing the time variability and the exceeding of the daily precipitation over various thresholds, which are indicators for the incidence of extreme rainfall events and by fitting the gamma distribution to the datasets per decade and for all the examined period, in order to reveal changes in the precipitation intensity.

## 2 Data and analysis

Daily precipitation totals recorded at 21 meteorological stations of the Hellenic National Meteorological Service for a 45-year period (1957–2001) were used for this study. The stations' network is satisfactorily distributed in Greek region (Fig. 1), representing well the precipitation of the country. The daily precipitation datasets give detailed report for the precipitation intensity and sufficient background for the evaluation of specific thresholds which provide more information about the trends and the time variability of extreme events.

First and foremost, the Factor Analysis (FA, S-mode) was applied to all available stations' datasets in order to reduce the number of variables and to detect structure in the relationships between variables that is to classify variables. Therefore each of the  $p$  initial variables (stations)  $X_1, X_2, \dots, X_p$  can be expressed as a linear function of  $m$  ( $m < p$ ) uncorrelated factors:  $X_i = a_{i1}F_1 + a_{i2}F_2 + \dots + a_{im}F_m$  where  $F_1, F_2, \dots, F_m$  are the factors and  $a_{i1}, a_{i2}, \dots, a_{im}$  ( $i=1, \dots, p$ ) are the factor loadings which express the correlation between the factors and the initial variables. The values of each factor are called factor scores and they are presented in standardized

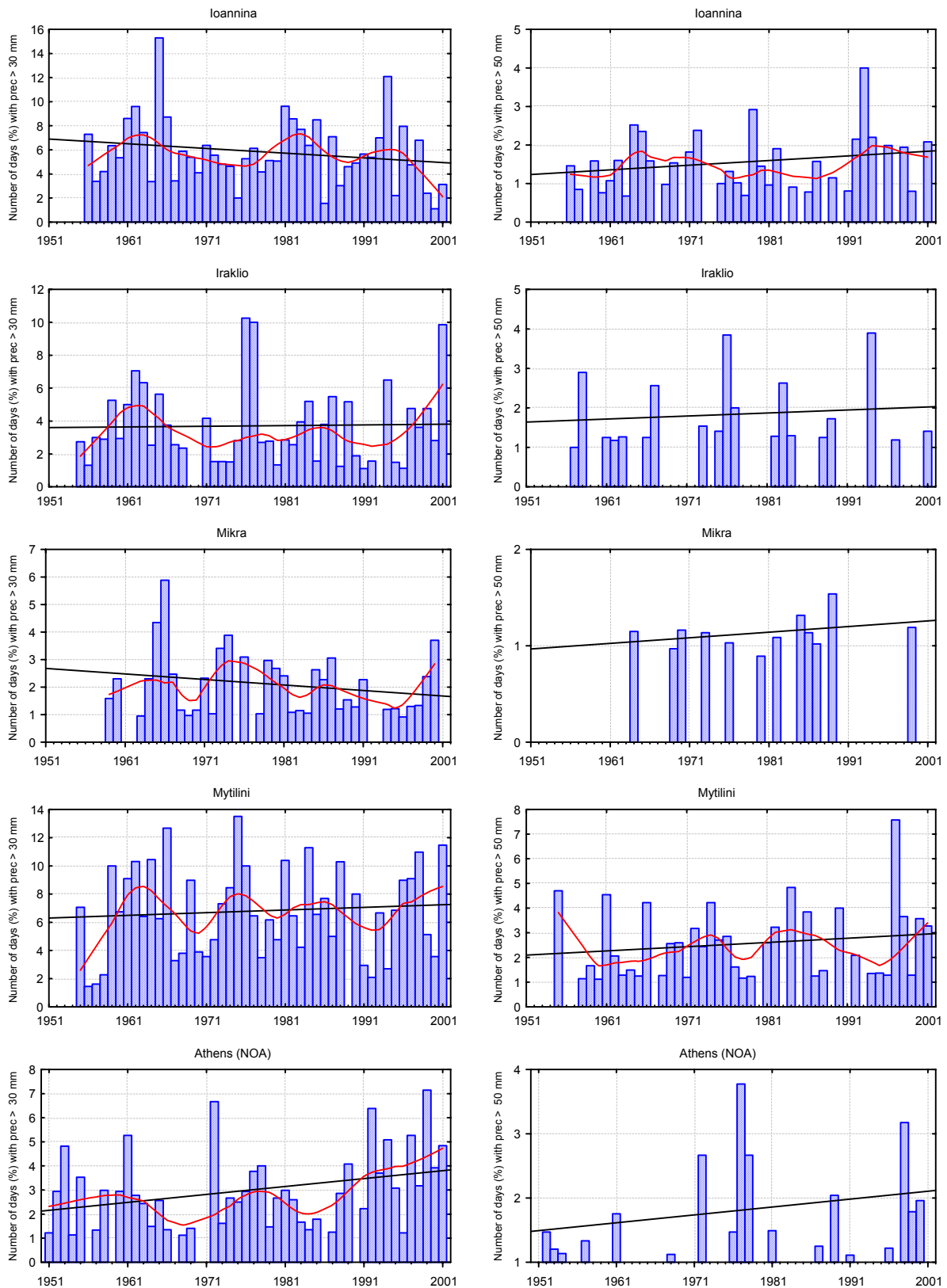
form, having zero mean and unit variance (Jolliffe, 1986). Another important point of the analysis is the rotation of the axes, which maximizes some factor loadings and minimizes some others and in that way a better separation among the initial variables is succeeded; for this reason Varimax rotation, which is generally accepted as the most accurate orthogonal rotation, was applied (Richman, 1986).

The second step was to examine, for representative stations within the regions extracted by FA, the temporal variability and trends of the time series of the number of precipitation days exceeding various thresholds such as 30 mm, (equal to the 95% percentile of daily precipitation for eastern and western regions and equal to the 97.5% percentile for the rest of the country) and 50 mm which is the threshold for very extreme and rare events. Especially the threshold of 50 mm is considered representative of very extreme rainfalls, by many researchers (Karl et al., 1995; Brunetti et al., 2004). The time variability for these constructed time series is estimated using the wavelet analysis (Torrence and Compo, 1998).

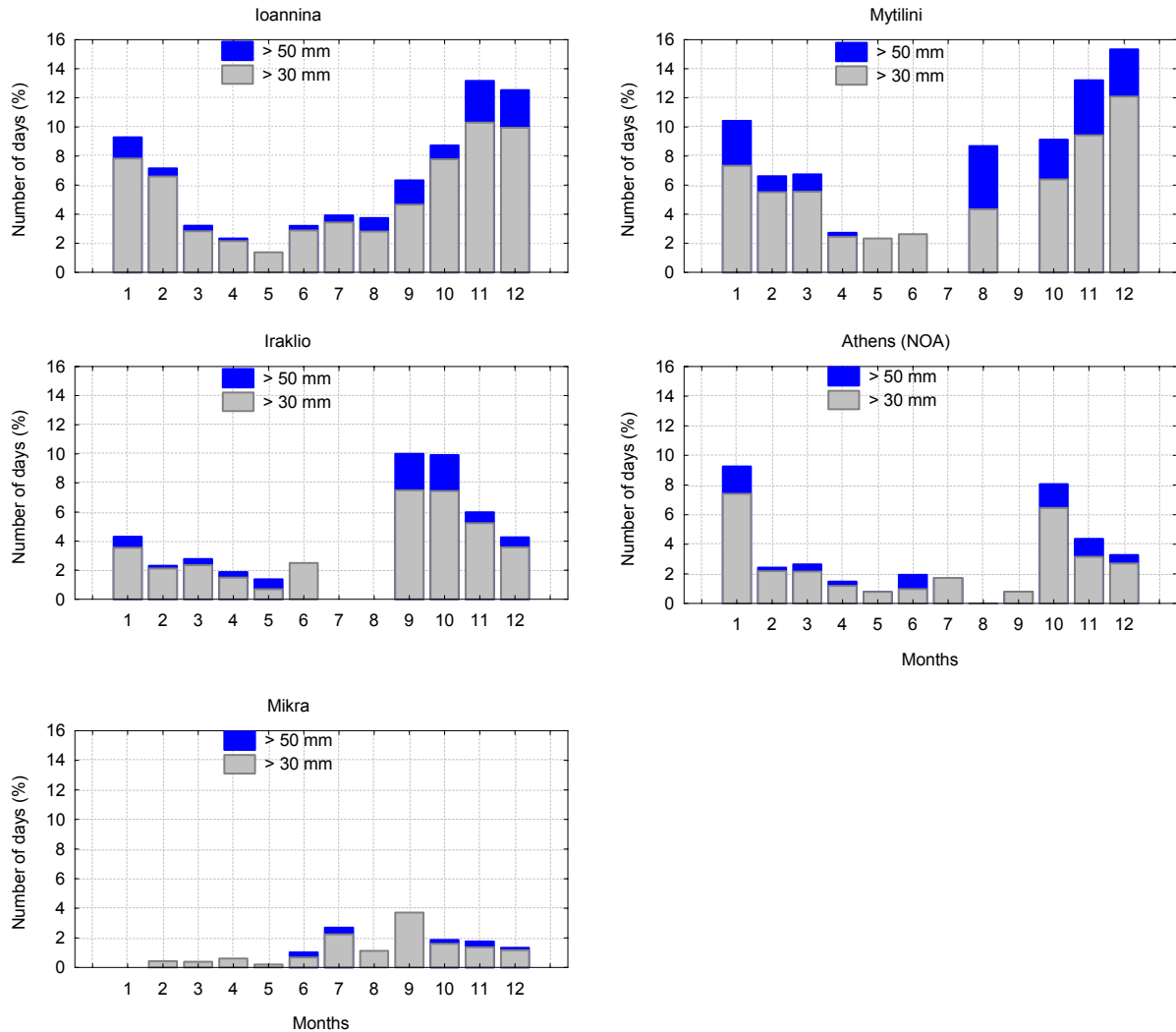
Finally, in order to estimate the probability of extreme events, the gamma distribution is applied to the daily precipitation datasets for the whole studied period and for the 10-year sub periods examining changes in the occurrence of the extreme events. The gamma distribution, which in addition is recommended by the World Meteorological Organization (Thom, 1971; Neyers, 1990), is the most appropriate for studies relative to precipitation distributions due to its moderately skewed profile (Thom, 1958; Wilks, 1995). Furthermore, the increase in the scale parameter  $\beta$  (appeared in the formula for the probability density function) results in stretching out the probability density distribution and therefore can be used in the determination of the probability of extreme events.

## 3 Results and discussion

The number of main factors (regions) was extracted by the application of FA on the monthly values of precipitation for the 21 meteorological stations, because FA is performed only in normal distributed variables. Five main factors (regions) with common precipitation characteristics were extracted by the application of FA, explaining 77% of the total variance. These represent the northern, southern, western, eastern and central regions of Greece (Fig. 1). For each such region, a representative station is selected for the analyses followed: Ioannina for western (1), Iraklio for southern (2), Mikra for northern (3), Mytilini for eastern (4) and Athens (National Observatory of Athens) for central (5) region. The representative station for each region was selected mainly as the station within the region with the highest factor loading. Firstly, the annual number of precipitation days exceeding the specific thresholds such as 30 mm and 50 mm was estimated. In the process, these values were divided by the respective number of the wet days for each year, and thereafter the



**Fig. 2.** Time series of the percentages (%) of the annual number of days with precipitation greater than 30 mm and 50 mm (annual number of days exceeding specified thresholds divided by the number of wet days of the year), along with linear and loess fitting.



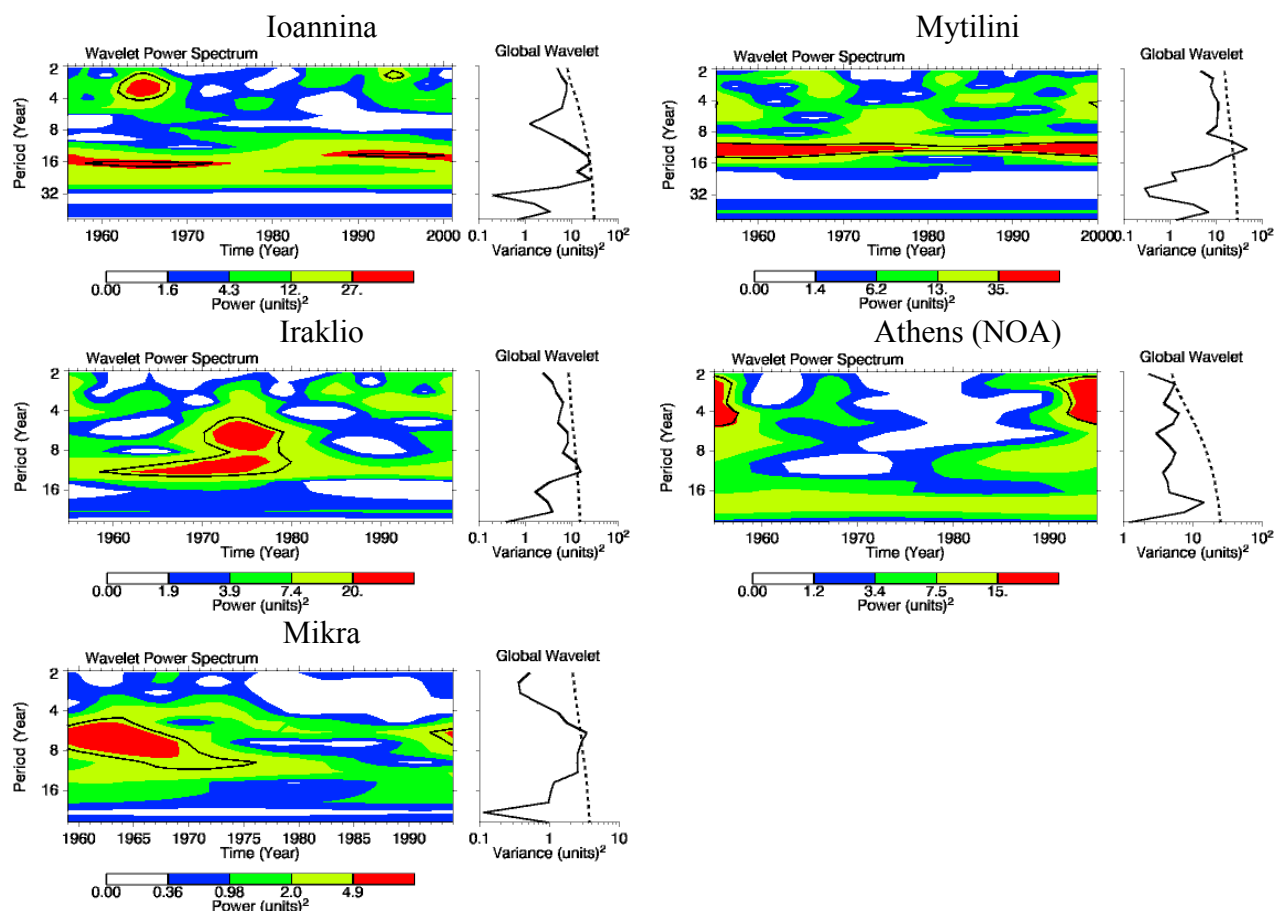
**Fig. 3.** Monthly distribution of the number of days (%) with precipitation greater than 30 mm and 50 mm (monthly number of days exceeding the specified thresholds divided by the number of wet days of the respective month).

percentages (%) of the annual number of precipitation days exceeding these thresholds were calculated (Fig. 2). Regarding the threshold of 30 mm, negative trends but statistically not significant (0.05 c.l.) appear in the western (Ioannina) and the northern (Mikra) regions, while rather stable trends appear in the southern (Iraklio) and the western (Mytilini) regions of Greece. Athens within the central region presents a statistically significant positive trend (0.05 c.l.), which has been pointed out in a previous study (Nastos and Zerefos, 2007). This is likely due to the urban heat island attributed to the extensive building of Athens after the Second World War and the rapid increase of the population and the number of vehicles mainly after 1970 (Philandras et al., 1999) combined with global warming during the recent decades.

On the one hand, warming is related to higher water content in the atmosphere (Douvillie et al., 2002; Trenberth et

al., 2003) and this has been evident in many regions (Sun et al., 2000; Ross and Elliott, 2001) resulted in an increase in the probability of severe convective weather (Bornstein and Lin, 2000; Guo et al., 2006). On the other hand, the extreme and rare events represented by the threshold of 50 mm appear a slight positive trend which is not statistically significant all over the country. Groisman et al. (2005) found that changes in heavy precipitation frequencies are always higher than changes in precipitation totals and, in some regions, an increase in heavy and/or very heavy precipitation occurred while no change or even a decrease in precipitation totals was observed.

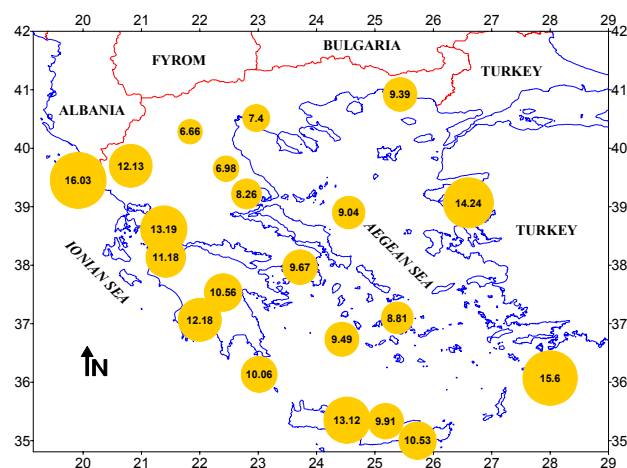
The monthly distributions of the percentages (%) of the number of days with precipitation greater than 30 and 50 mm, for the representative stations from the regions extracted, are depicted in the stacked graphs of the Fig. 3. The extreme and



**Fig. 4.** The wavelet power spectrum (left graph) and the global wavelet power spectrum (right graph) for the time series of the annual number of days (%) with precipitation greater than 30 mm.

rare precipitation events appear mainly during winter months with respect to western and eastern regions and specifically the days (%) with precipitation greater than 50 mm turn up more frequent within the eastern region (Mytilini) while are also more evident in August. Regarding the southern region, the extreme events appear their peaks during autumn months (September to October) while their occurrence is minimized in summer. In northern region, the precipitation extremes are diminished and are obvious especially in July and September, while in Athens the peaks appear in January and October.

In the process, wavelet analysis (Torrence and Compo, 1998) is used to identify variations in temporal cycles in the extreme precipitation events and furthermore to find relationships between these extremes and the dominant modes of the climate variability. Wavelet analysis was applied only in the time series of the annual number of days (%) with precipitation greater than 30 mm and not in the time series with the threshold of 50 mm, because these time series appear a lot of gaps and a small sample size, due to the rareness of these very extreme events. The analysis of climate extremes and their changes requires a very careful procedure. There is



**Fig. 5.** Spatial distribution of the scale parameter of the gamma distribution fitted to daily precipitation totals.

**Table 1.** Parameters of the gamma distribution fitted to daily precipitation data for the whole examined period (1957–2001).

Stations	ObservedMean	Observed Variance	Scale	Shape	Stations	ObservedMean	ObservedVariance	Scale	Shape
1. Kozani	5.58	53.45	6.66	0.84	11. Kythira	7.35	106.15	10.06	0.73
2. Larissa	5.16	64.12	6.98	0.74	12. Ierapetra	8.29	148.05	10.53	0.79
3. Mikra	5.42	58.70	7.40	0.73	13. Tripolis	7.84	102.40	10.56	0.74
4. Agchialos	5.97	85.29	8.26	0.72	14. Araxos	8.32	110.81	11.18	0.74
5. Naxos	5.99	76.89	8.81	0.68	15. Ioannina	9.39	125.97	12.13	0.77
6. Skyros	6.66	84.51	9.04	0.74	16. Kalamata	8.34	140.21	12.18	0.68
7. Alexandroupolis	6.42	92.04	9.39	0.68	17. Rethymno	9.22	179.02	13.12	0.70
8. Milos	7.02	95.49	9.49	0.74	18. Agrinio	9.71	160.51	13.19	0.74
9. Athens (NOA)	6.23	94.93	9.67	0.64	19. Mytilini	9.57	179.97	14.24	0.67
10. Iraklio	6.95	100.02	9.91	0.70	20. Rhodes	10.16	250.14	15.60	0.65
					21. Kerkyra	10.69	226.40	16.03	0.67

**Table 2.** Parameters of the gamma distribution fitted to daily precipitation data of representative stations in the western and southeastern regions, for 10-year sub periods.

Stations	ObservedMean	Observed Variance	Scale	Shape
(Western region) Janina				
1961–1970	10.26	129.86	12.08	0.84
1971–1980	9.14	116.77	11.74	0.78
1981–1990	8.92	119.49	11.93	0.75
1991–2000	8.88	135.61	12.26	0.72
(Western region) Kerkyra				
1961–1970	10.67	228.43	16.47	0.65
1971–1980	10.63	201.87	15.16	0.70
1981–1990	10.20	195.40	14.77	0.69
1991–2000	10.68	240.06	16.52	0.65
(Southeastern region) Rhodes				
1961–1970	9.51	183.32	14.39	0.66
1971–1980	9.95	209.02	15.58	0.64
1981–1990	9.92	274.22	15.52	0.64
1991–2000	11.26	337.97	17.59	0.64

large uncertainty in the estimate of extremes, simply because they represent infrequent events with small sample size.

The wavelet power spectrum and the global wavelet power spectrum for the time series of the annual number of days (%) with precipitation greater than 30 mm are depicted in Fig. 4. The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively. Black contour is the 5% significance level, using a red-noise (autoregressive lag1) background spectrum. The dashed line is the significance level for the global wavelet spectrum, assuming the same significance level and background spectrum as in left graph. Wavelet analysis shows that decadal cycles (10 to 16 years), statistically significant (0.05 c.l.), dominate in the western and eastern regions, concerning the whole examined period. Moreover, 2–10 year periods are exhibited all over the country with less or more significance with respect to time.

The negative correlation between the number of days with precipitation greater than 30 mm and the North Atlantic Oscillation Index for December, January, February and March seems to be small ( $\sim -0.2$ ) and not statistically significant (at 0.05 c.l.).

The probability of the extreme events is well determined by the scale and shape parameters of the fitted gamma distribution. The results show that the shape parameter of the precipitation gamma distributions remains rather stable in this period of study, independent of the total precipitation, while the scale parameter, which characterizes the scale of the intensity of the daily precipitation (the higher the scale parameter is, the higher the intensity is), is most variable (Fig. 5). High figures of the scale parameter appear in the western, eastern and southeastern Greece, while low ones appear mainly in the central continental Greece. Table 1 presents the parameters of the fitted gamma distribution along with the



observed mean and variance for each station included in the analysis. The fitted gamma distributions to the precipitation datasets within 10-year sub periods indicate that increased scale parameter and observed variance appear for the western and southeastern regions (Table 2), especially during the last decade 1991–2000. The scale parameter and the observed variance are rather constant or of low variability for the rest stations of the country (not shown for brevity's sake).

#### 4 Conclusions

The analysis of the extreme daily precipitation totals in Greece demonstrates the existence of positive trends, not statistically significant (0.05 c.l.), observed in daily precipitation totals exceeding 30 and 50 mm at the eastern and southeastern regions of the country. The application of the wavelet analysis to the time series of the number of days exceeding the above thresholds resulted in significant quasi biennial and quasi decadal periods. The extreme precipitation events appear during winter months in the western and eastern regions, and mainly during autumn in the rest of the country. Moreover, the fitted gamma distributions to the daily precipitation totals with respect to the 45-year period (1957–2001) reveal that high figures of the scale parameter appear in the western, eastern and south-eastern Greece, while low ones appear mainly in the central continental Greece. Regarding the 10-year sub periods, we found that increased observed variance and scale parameter are appeared in the western and southern-eastern regions, especially during the last decade 1991–2000, indicating the incidence of extreme daily precipitation.

Edited by: S. C. Michaelides

Reviewed by: two anonymous referees

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